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THz generation by optical rectification involving high-index planes

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THz Generation by Optical Rectification Involving High-Index Planes

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***Abstract*—We report a theoretical and experimental study of the generation of THz radiation by optical rectification from high-index planes of GaAs crystals.**

I. Introduction

THE generation of terahertz-frequency electromagnetic radiation by the phenomenon of optical rectification has been known for some time. As far back as 1995 a detailed experimental and theoretical study was presented [1] that included a discussion of the optical rectification in zinc blende crystals in transmission geometry. In this configuration, the simplest crystal orientation of (100) produces no optical rectification, but the next simplest orientations, (110) and (111), were discussed. At about the same time, mid-infrared emission by optical rectification from (110) crystals was also reported [2]. In reflection geometry, coupling to the (100) faces is permitted. However, in reflection geometry, as well as optical rectification, current surge effects can result in terahertz generation, which can complicate the interpretation of the optical rectification effects. Reports on reflection geometry also first treated low-index faces, such as (111) [3,4] and (100) [4]. To further explicate the mechanisms involved, second-harmonic generation has been simultaneously studied with THz emission, but again restricted to (100), (110), and (111) faces [5]. Recently a report on (112) faces of InSb in the reflection geometry has appeared [6]. The main result of that work is that bulk optical rectification alone could not account for the experimental results, but that the surface electric-field-induced optical rectification also needed to be included. In the present study we extend the work to higher-index faces, specifically to those of form (11*n*).

II. Theory

Tracing the pump beam into the crystal then the generated THz radiation out of it involves several changes of coordinate system. First, the components of the pump beam are specified in the laboratory frame of reference. Next, the components of the pump beam are calculated in the crystal frame of reference. Then, the nonlinear polarization is calculated. Finally, the components of the polarization vector in the laboratory frame of reference are determined. These are assumed to be proportional to the THz electric field, in the far-field approximation. Further generalization occurs if the polarization of the pump beam is considered (that is, if the pump beam contains both *p* and *s* components) and if the detector is placed at an arbitrary position relative to the sample surface. We have solved this problem in general.

Restricting the discussion now to planes of the form (11*n*), the crystal transformation matrices involve terms including the root of $n^2 + 1$ and $n^2 + 2$. So, for example, for (113) the transformation matrix is:

$$\begin{pmatrix} 3/\sqrt{11} & -1/\sqrt{10} & -3/\sqrt{110} \\ 1/\sqrt{11} & 3/\sqrt{10} & -1/\sqrt{110} \\ 1/\sqrt{11} & 0 & \sqrt{10}/\sqrt{11} \end{pmatrix}.$$

Regardless of the index, the highest order terms which occur in the expressions for the azimuthal angle θ dependence of the terahertz emission involve $\cos 3\theta$ and $\sin 3\theta$. This is true for both transmission and reflection geometry.

III. Experiment

We have performed time-domain spectroscopy experiments using ultrashort (<12 fs) laser pulses generated by a Ti:sapphire laser of center wavelength 790 nm. In our experiments, the pump beam is horizontally (*p*) polarized as it strikes the semiconductor emitter sample. The samples used are GaAs oriented along either (110), (111), (112), (113), (114), or (115) faces. The incidence angle is either 0 or 45° and the THz radiation is detected in the straight-through and specular reflection directions, respectively. The samples are rotated around the surface normal and the THz radiation measured as a function of the azimuthal angle. The THz radiation generated is passed through a wire-grid polarizer. We separately examine the components horizontally (or *p*) and vertically (or *s*) polarized.

IV. Results and Discussion

The THz field detected as a function of azimuthal angle for the two polarizations varies systematically with the index *n* in the manner predicted by the theory over the samples studied. Both *A* (Ga-rich) and *B* (As-rich) faces have been studied. We give in Figs. 1 and 2 data from the (113)*B* faces of GaAs for *s* and *p* polarized emitted radiation, respectively. Time domain spectra were collected at sixty-one azimuthal angles, separated successively by 6°. (The first and last spectra coincide in azimuthal angle). The *s*-polarized data, Fig. 1, is symmetrically displaced about the zero of the vertical (or detector signal) axis. In contrast, the *p*-polarized radiation, Fig. 2, is offset. In this case, as well as the optical rectification effect, which gives the modulation, there is a current surge component, which gives the offset.

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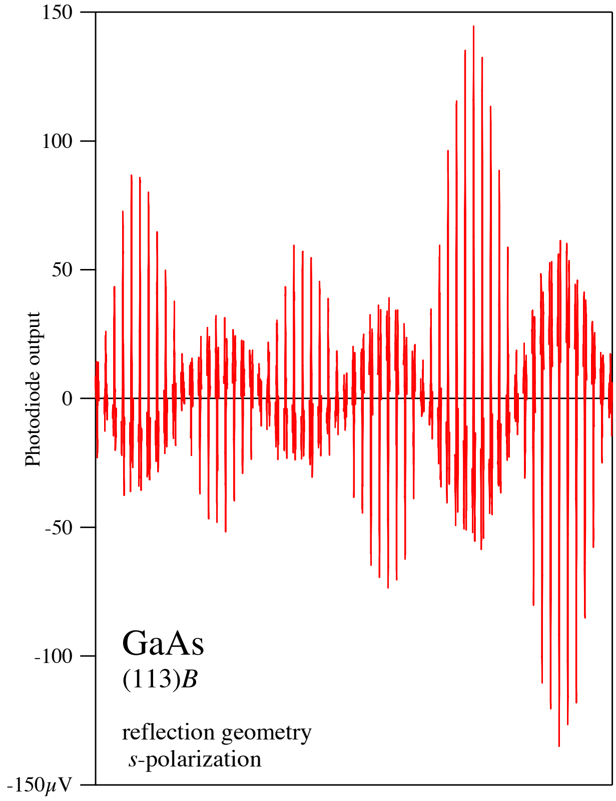

Fig. 1. Time-domain spectra from GaAs (113)*B* face in reflection geometry (pump radiation *p* polarized, emitted radiation *s* polarized) for sixty-one different azimuthal angles, each separated by 6°. The successive spectra are offset in the horizontal direction for clarity. The vertical axis is the same for all spectra, and one quarter that of Fig. 2.

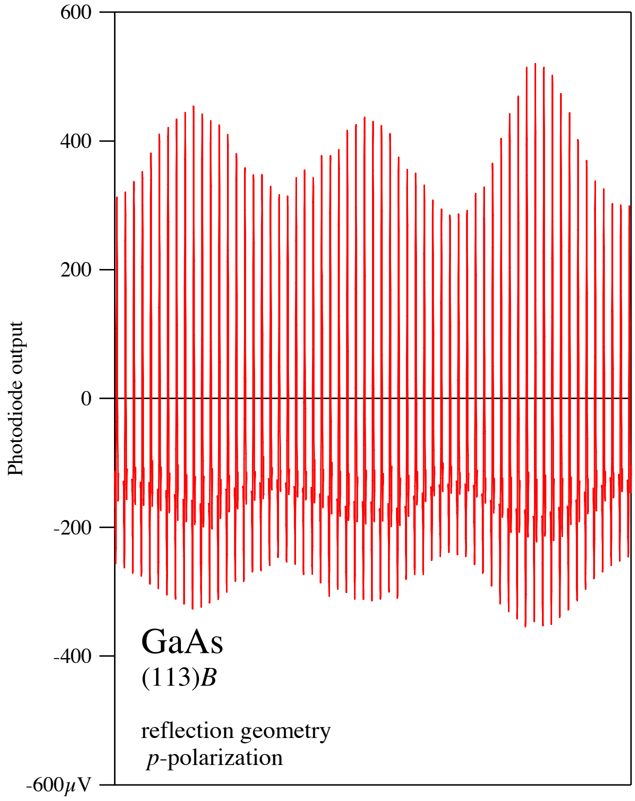

Fig. 2. Time-domain spectra from GaAs (113)*B* face in reflection geometry (pump radiation *p* polarized, emitted radiation *p* polarized) for sixty-one different azimuthal angles, each separated by 6°. The successive spectra are offset in the horizontal direction for clarity. The vertical axis is the same for all spectra, and four times that of Fig. 1.

We now concentrate on the optical rectification component. Related to the work on InAs [5], and as with the work for InSb [6], we find both bulk and surface contributions to the optical rectification are necessary to account for the results. We have also demonstrated this to be the case for GaBiAs [7], and furthermore in that case that the optical rectification differs at the *A* and *B* faces. The azimuthal angle dependence, supported by the dependence on optical fluence and on in-plane magnetic field, indicate that in that case the main contribution to terahertz generation is optical rectification and not transient currents [7].

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